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Ionization history of the cosmic plasma in the light of the recent CBI and future PLANCK data.

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ABSTRACT

The paper is devoted to the methods of determination of the cosmological parameters from recent CMB observations. We show that the more complex models of kinetics of recombination with a few "missing" parameters describing the recombination process provide better agreement between measured and expected characteristics of the CMB anisotropy. In particular, we consider the external sources of the $Ly-\alpha$ and $Ly-c$ radiation and the model with the strong clustering of baryonic component. These factors can constrain the estimates of the cosmological parameters usually discussed. We demonstrate also that the measurements of polarization can improve these estimates and, for the precision expected for the PLANCK mission, allow to discriminate a wide class of models.

Subject headings: theory: – cosmic microwave background – ionization

1. Introduction

Recent observations of the CMB anisotropy (the BOOMERANG, de Bernardis et al. 2000; MAXIMA-1, Hanany et al. 2000; DASI, Halverson et al. 2001, VSA, Watson et al. 2002) and in particular the new CBI data (Mason et al. 2002) provide the good base for our understanding of the most general properties of the Universe. In these experiments, major attention is focused on the statistical properties of the signal and the determination of the power spectrum of the CMB anisotropy. For the most probable value of the Hubble constant $h = H_0/100km/s/Mpc) \simeq 0.65 - 0.70$, all teams have reported the best fit parameters of the cosmological models. These parameters are the most probable values of the baryonic, Ω_b, and cold dark matter, Ω_c, density, the density of the vacuum Ω_Λ, the curvature parameter Ω_K, possible tilt of the power spectrum of the adiabatic perturbations, n_s, the optical depth after the reionization, τ_r, and so on. The precision of the measurements allows to discuss and to reveal some distortions of the standard model of the recombination process occurred at redshifts $z \simeq 10^3$.

For the baryon dominated Universe the classical theory of the hydrogen recombination was developed in Peebles (1968) and Zel'dovich, Kurt and Sunyaev (1968). For the dark matter dominated Universe, it was generalized in Zabotin and Naselsky (1982), Jones and Wyse (1985), Seager, Sasselov and Scott (1999) and others (see also review in White, Scott and Silk, 1994).

Many distortions of the standard model of recombination has also been discussed. The delay of recombination due to the evaporation of the primordial black holes has been discussed in Naselsky (1978) and Naselsky and Polnarev (1987). Avelini et al. (2000), Battye et al. (2001), Landau et al. (2001) pointed out that possible time variations of the fundamental constants could also be a crucial factor for ionization history of the cosmic plasma. Sarkar and Cooper (1983), Scott et al. (1991), Ellis et al.

(1992), Adams et al. (1998), Peebles, Seager and Hu (2000), Doroshkevich and Naselsky (2002) discussed distortions of the kinetics of the hydrogen recombination caused by decays of hypotetical unstable particles. It is worth noting that for such models the energy injection delays the recombination at $z \simeq 10^3$ and distorts the ionization history of the Universe up to the period of galaxy formation at $z \simeq 5 - 10$.

Recently Naselsky and Novikov (2002) have proposed the clumpy baryonic model with more complex recombination process. As compared with the standard model with the same cosmological parameters, in this model the recombination proceeds faster within clumps and slowly in the intercloud medium. Here we show that, with suitable parameters for such clouds, such class of models provides a better fit of the observed power spectrum of the CMB anisotropy.

In this paper we compare the observed CMB power spectrum in two reference models with the standard recombination and in two models with distorted recombination. We show that the later provides better fits of the observed power spectrum and consequently change the estimates of the cosmological parameters. Moreover the measurements of polarization allow to discriminate between some of such more complex models of the Universe. These results can be important for the interpretation of the future MAP and PLANCK data.

The structure of the paper is as follows. In section 2 we discuss the generic models of the distorted recombination and the redshift variations of the hydrogen ionization fraction in these models. In section 3 we compare the observed CMB anisotropies and expected polarization power spectra with ones for the models under discussion. In Conclusion we make some useful predictions for the MAP and future PLANCK experiments.

2. Deviations from the standard model of hydrogen recombination

The deviations from the standard recombination process can be caused by the injection of additional Ly-α and Ly-c photons at the recombination epoch or by the strong small scale clustering of baryonic component. The distortions of the recombination kinetics can be described in terms of an additional source of Ly-α and Ly-c photons. The properties of all such models can be suitably described using the Peebles, Seager and Hu (2000) approach. In the generalized model the rates of production of resonance, n_α, and ionized, n_i, photons are described by functions, $\varepsilon_\alpha(z)$ and $\varepsilon_i(z)$, defined as follows:

$$\frac{dn_\alpha}{dt} = \varepsilon_\alpha(z) H(z) \langle n_b \rangle \,, \qquad (1)$$

$$\frac{dn_i}{dt} = \varepsilon_i(z) H(z) \langle n_b(z) \rangle \,, \qquad (2)$$

where $H(z)$ and $\langle n_b(z) \rangle$ are the Hubble parameter and the mean baryonic density, respectively.

In Peebles, Seager and Hu (2000) the models with $\varepsilon_\alpha(z) = const.$ and $\varepsilon_i(z) = const.$ were considered. However, as was shown in Doroshkevich and Naselsky (2002), in the model with generation of ionized photons from the decay of Super heavy dark matter particles we get $\varepsilon_\alpha(z) \sim \varepsilon_i(z) \propto (1+z)^{-1}$. Indeed, for many models of the particle decays the particle number density, n_x, is decrising in time as

$$\frac{dn_x}{dt} + 3H(t) n_x = -\frac{n_x}{\tau_x(n_x, t)} \qquad (3)$$

where $\tau_x(n_x, t)$ is the life time of the particles. For the simplest models with $\tau_x = const.$ we have

$$\frac{d[n_x(1+z)^3]}{dt} = \varepsilon_x(t) H(t) \langle n_b \rangle \,, \qquad (4)$$

$$\varepsilon_x = -\frac{1}{H(z)\tau_x} \exp\left(-\frac{t - t_U}{\tau_x}\right) \frac{n_x(t_U)}{\langle n_b(z) \rangle} \,,$$

where t_U is the age of the Universe. Obviously, $\varepsilon_i = \kappa_i \varepsilon_x$, $\varepsilon_\alpha = \kappa_\alpha \varepsilon_x$ where factors κ_i and κ_α characterize the efficiency of transformation of decay products to resonance and ionized photons.

For all models with a decay and/or an annihilation of heavy particles, with evaporation of primordial black holes (Naselsky and Polnarev 1987) as well as for the models with the strong small scale clustering of the baryonic component (Naselsky and Novikov 2002) the functions ε_α and ε_i can be written as follows:

$$\varepsilon_{i,\alpha}(z) \propto \sum_j \exp[-\zeta^{m_j}] c_j^{i,\alpha} \zeta^{n_j} \,, \qquad (5)$$

$$\zeta = (1+z)/(1+z_d)\,,$$

where parameters $c_j^{i,\alpha}, z_d, m_j,$ and n_j characterize the j^{th} source of radiations.

Naturally we expect that $\varepsilon_i(z) \geq 0$ for all redshifts $z \leq 10^3$. This additional ionization process suppresses partly the CMB anisotropy because of the growth of the optical depth for the Compton scattering.

Three scenarios can be discussed depending upon the shape of the function $\varepsilon_\alpha(z)$. Thus, $\varepsilon_\alpha(z) \geq 0$ and $\varepsilon_\alpha(z) \leq 0$ describe the delay or acceleration of recombination. If, however, $\varepsilon_\alpha(z) \leq 0$ for redshifts $z \geq z_r$, and $\varepsilon_\alpha(z) \geq 0$ for redshifts $z \leq z_r$, then the acceleration of the recombination at $z \geq z_r$ is accompanied by the delay of recombination at $z \leq z_r$.

All these scenarios can be based on the realistic physical models. For example, for the decay of the long lived Super heavy dark matter particles (SHDM) discussed in Doroshkevich and Naselsky (2002) we get

$$\varepsilon_i \propto (1+z)^{-1}, \quad \varepsilon_\alpha \sim \varepsilon_i\,, \tag{6}$$

that corresponds to the first scenario. The same scenario is realized for the decay of other kinds of the SHDM particles described by an expression

$$\varepsilon_i \propto (1+z)^{\nu-1}, \quad \varepsilon_\alpha \sim \varepsilon_i\,, \tag{7}$$

with $\nu \geq -1$. For the model with the evaporation of primeval black holes we have for parameters in (5) $m = n \approx -3/2$ and $z_d \approx 10^3$. Third scenario is realized for the clumpy baryonic model discussed below. The list of the physical models can be essentially extended.

2.1. Four models with different ionization history

To illustrate the possible impact of the external sources of resonance and ionized photons we consider four models with different baryonic density and different sources of unequilibrium photons. All four models are based on the spatially flat ΛCDM cosmological model with $\Omega_K = 0$ and with

$$\Omega_\Lambda = 0.7,\ \Omega_c + \Omega_b = 0.3,\ h = 0.7,\ n_s = 1, \tag{8}$$

where n_s is the power index for the initial power spectrum.

For the reference models 1 and 2 we have to use the baryonic and DM densities $\Omega_b h^2 = 0.022$, $\Omega_c h^2 = 0.125$ and $\Omega_b h^2 = 0.032$, $\Omega_c h^2 = 0.115$, respectively, and assume the standard ionization history with $\varepsilon_i = \varepsilon_\alpha = 0$ and the optical depth for the Compton scattering at the period of the reionization of the Universe $\tau_r = 0.1$. These models differ by the density of the baryonic and DM component only. The redshift variations of the ionization fractions, x_1 and x_2, for these models plotted in Fig. 1 are quite similar. As is seen from Fig. 1, the relative difference between the ionization fractions,

$$x_{12} = 2(x_1 - x_2)/(x_1 + x_2)\,, \tag{9}$$

also plotted in Fig. 1 does not exceed 20% at $z \leq 10^3$ and achieves $\sim 30\%$ at lower redshifts. Non the less, even such limited variations produce measurable differences of the CMB anisotropy.

The model 3 is the clumpy baryonic models with $\langle \Omega_b h^2 \rangle = 0.022$, $\Omega_c h^2 = 0.125$ and with the density contrast between the clouds and intercloud medium $\xi = \rho_{in}/\rho_{out} = 11$. We assume that the clouds occupy the fraction of volume $f_v = 0.1$ and accumulate the mass fraction $f_m = \xi f_v [1 + (\xi - 1) f_v]^{-1} \approx 0.5$. We assume also that the mass function of the clouds is close to the delta function, $\delta(M - M_{cl})$, with $10^2 M_\odot \leq M_{cl} \leq 10^6 M_\odot$ (Naselsky and Novikov, 2002). For this model, we neglect the Compton scattering after reionization of the Universe and $\tau_r \sim 0.1$ is gained at redshifts $0 \leq z \leq 10^3$.

The model 4 differs from the model 2 by external sources of ionization described as follows:

$$\begin{aligned} \varepsilon_\alpha(x) &= \alpha \zeta^{-3/2} \exp[-\zeta^{-3/2}]; \\ \varepsilon_i(z) &= \beta \zeta^{-3/2} \exp[-\zeta^{-3/2}]\,, \end{aligned} \tag{10}$$

where $\alpha \simeq 0.3$, $\beta \simeq 0.13$ and $\zeta = (1+z)/(1+z_d) \simeq z \cdot 10^{-3}$. These parameters coincide with the model of evaporation of primordial black holes. This model is quite similar to the model of unstable Super heavy dark matter particles discussed in Doroshkevich and Naselsky (2002). As in the previous model 3, $\tau_r \sim 0.1$ is gained at redshifts $10 \leq z \leq 10^3$.

2.2. Recombination of the hydrogen in models 3 and 4

As was noted above, for the models 1 and 2 the recombination process is quite similar but for more complex models 3 and 4 more strong deviations appear. Thus, for the clumpy baryonic model (model 3) the recombination within clouds occurs earlier than in the intercloud medium and, so, for comparison with the reference model 1 we have to use the mean ionization fraction and its relative difference from the fraction x_1,

$$x_{mean} = x_{in} f_m + x_{out}(1 - f_m)\,,$$
$$x_{13} = 2(x_1 - x_{mean})/(x_1 + x_{mean})\,. \qquad (11)$$

Here f_m is the mass function accumulated by clouds and x_{in} and x_{out} are the ionization fractions within clouds and in intercloud medium. As is seen from Fig. 2, in spite of the strong difference between $x_{in}(z)$ and $x_{out}(z)$ the difference between x_1 and x_{mean} is quite moderate. However, as is seen from Fig. 3, redshift variations of the relative difference of these fractions are quite complex. At redshifts $z \geq 700$ the recombination is accelerated while at $z \leq 700$ it is delayed, and $x_{13} \sim 20\%$ is achieved already at $z \sim 1200 - 1300$, at the period of formation of higher multipoles of CMB anisotropy.

For model 4 the redshift variations of the ionization fraction, $x_4(z)$, are plotted in Fig. 4 in comparison with ones for the reference models 1 and 2. As is seen from Fig. 4, the redshift variations of the relative difference of the ionization fractions,

$$x_{14} = 2(x_4 - x_1)/(x_4 + x_1),$$
$$x_{24} = 2(x_4 - x_2)/(x_4 + x_2)\,, \qquad (12)$$

achieve ~ 20 – 30% already at $z \sim 10^3$ and become very significant at $z \leq 10^3$. Let us note, that the stronger ionization obtained in the model 4 at $z \leq 800$ provides the growth of the optical depth for the Compton scattering that suppresses the amplitude of the CMB anisotropy. However, relatively small perturbations of the recombination process at $z \geq 10^3$ restrict the possible shifts of high multipoles of the CMB anisotropy.

The same effects were noted for the model with the decay of Super heave DM particles (Doroshkevich and Naselsky, 2002).

They are typical for all scenario with moderate ε_α and, for the same optical depth $\tau_r \sim 0.1$, they are weakly dependent upon a detailed form of function ε_i.

These results show that we can expect noticeable variations of the CMB anisotropy for models 3 and 4 as compared with models 1 and 2 .

3. Anisotropy and polarization as a test of the history of ionization.

To obtain the power spectra of the CMB anisotropy and polarization in our models we have to use the modification of the CMBFAST code (Seljak and Zaldarriaga, 1996) taking into account more complicated ionization history of the Universe. For the reference models 1 and 2, we use the standard CMBFAST code for the optical depth τ_r and the ionization fraction $x = 1$ achieved at the redshift of reionization, z_r, with

$$z_r = 13.6\left(\frac{\tau_r}{0.1}\right)^{2/3}\left(\frac{1-Y_p}{0.76}\right)^{-2/3}\left(\frac{\Omega_b h^2}{0.022}\right)^{-2/3}\left(\frac{\Omega_c h^2}{0.125}\right)^{1/3} \quad (13)$$

where Y_p is the helium mass fraction of the matter.

In Fig.5 we plot the CMB power spectrum for the models 1-4 in comparison with data from the BOOMERANG, MAXIMA-1, and CBI (Mason et al, 2002) data at the multipole range $l \leq 2\ 000$ where the possible influence of the Sunyaev-Zel'dovich effect is not yet important.

As one can see from Fig. 5, all the models look very similar to each other. The quality of models can be characterized quantitatively by the χ^2-parameter listed in Table 1 for all models. Here the reference model 1 provides the best fit for the CBI data for the standard ionization history while for the reference model 2 $\chi^2_2 \geq \chi^2_1$. However, the model 3 demonstrates an excellent agreement with the CBI data, $\chi^2_3 = 0.5\chi^2_1$, and $\chi^2_3 \leq \chi^2_1$ for other observations. For the model 4 with larger baryonic density we get also $\chi^2_4 \leq \chi^2_1$ for the CBI data and only for the BOOMERANG data $\chi^2_4 \geq \chi^2_1$.

The models 1, 3 and 4 are quite

consistent with available measurements of $C(l)$. This means that the more complicated ionization history of hydrogen violates the standard fit procedure and, most of all, makes it ambiguous the determination of the baryonic density from the CMB measurements. This fact is very important for the interpretation of the future MAP and PLANCK measurements.

To characterize the differences between the models and to compare them with the expected sensitivity of the PLANCK experiment we plot in Fig. 6 the functions

$$D_{13}(l) = 2\left[C_1(l) - C_3(l)\right] / \left[C_1(l) + C_3(l)\right] \ ,$$
$$D_{24}(l) = 2\left[C_2(l) - C_2(l)\right] / \left[C_2(l) + C_2(l)\right] \ , \qquad (14)$$

for the multipole range $2 \le l \le 2\ 500$. These functions can be directly compared with the expected error bars of $C(l)$ for the future PLANCK mission.

As is clear from Fig. 6, $D_{13}(l) \le 0.05$ and $D_{24}(l) \le 0.05$ and they can be reduced at least up to 0.02 for lower ε_α and ε_i and after fine tuning of the 'missing parameters' of the CMB anisotropy formation such as ξ, f_v, M_{cl} and other introduced in Sec. 2. These 'missing' parameters significantly increase the total number of fit parameters of the CMB power spectrum and lead to the ambiguous interpretation.

The polarization measurements allow to improve somewhat the interpretation. The polarization power spectra, $\Delta T_p^2(l) = l(l+1)C_p(l)/2\pi$, are plotted in Fig. 7 for all four models. As is seen from this Fig. the differences between these spectra are small at $l > 200$. But the bump at $l \sim$ 5-10 related to the hydrogen reionization at the epoch of galaxies formation, $z \sim 8 - 10$, can be essentially suppressed for models 3 and 4 wherein the required optical depth is gained at redshifts $z \sim 100 - 500$.

However, for the PLANCK mission one of the most important source of uncertainties at $l \le 200$ is the cosmic variance. For this range, the expected errors of the $\Delta T_p^2(l)$ is estimated as

$$\delta C_p(l)/C_p(l) \simeq (f_{sky} l)^{-1/2} \simeq$$
$$9\,(l/200)^{-1/2}\,(f_{sky}/0.65)^{-1/2}\,\% \, . \qquad (15)$$

Here we assume that instrumental noise and systematics should be close to the cosmic variance limit at the multipole range of interest. For $f_{sky}/0.65 \simeq 1$ and $l \simeq 2\ 000$ the cosmic variance limit is $\delta C(l)/C(l) \simeq 3\%$ at 68% confidential level, and all peculiarities of the anisotropy power spectra under this limit should be unobservable. As it follows from Fig. 8 for the CMB polarization, all features of the power spectrum can be observed by the PLANCK and, probably, the low multipole part of the power spectrum can be observed already by the MAP mission. This means that future polarization experiments can be crucial for investigation of the ionization history of the cosmic plasma and possible distortions of the kinetics of hydrogen recombination at high redshifts.

4. Conclusion

The precision of measurements of the CMB anisotropy, both already achieved and especially expected for the MAP and PLANCK missions, allows to extend the class of cosmological models under consideration and to discuss some distortions of the standard model of the recombination process occurring at redshifts $z \simeq 10^3$. Many physical models can be considered as a basis for such discussions.

In this paper we compare available observations of the CMB anisotropy with those expected in several models with different kinetics of recombination. These difference can be caused by possible external sources of the resonance and ionized radiation, the possible small scale clustering of the baryonic component and other factors.

We show that such extension of the cosmological models increases the number of parameters using to fit observed power spectra of the anisotropy and, in perspective, of the polarization. We show that the influence of these "missing" parameters can essentially improve the fits used and, in particular, to obtain better agreement between the observed and expected positions and amplitudes of peaks for higher multipoles. At the same time, including of the "missing" parameters changes the measured values of cosmological parameters usually discussed.

We show also that the expected sensitivity of the PLANK mission in respect to the measurements of the polarization will allow to discriminate between main families of such models and, in particular, between models with small and large optical depth at redshifts $10^3 \geq z \geq 20 - 100$. We would like to note that realistic values of the cosmological parameters can not be obtained from the CMB data without the PLANCK observations of the polarization.

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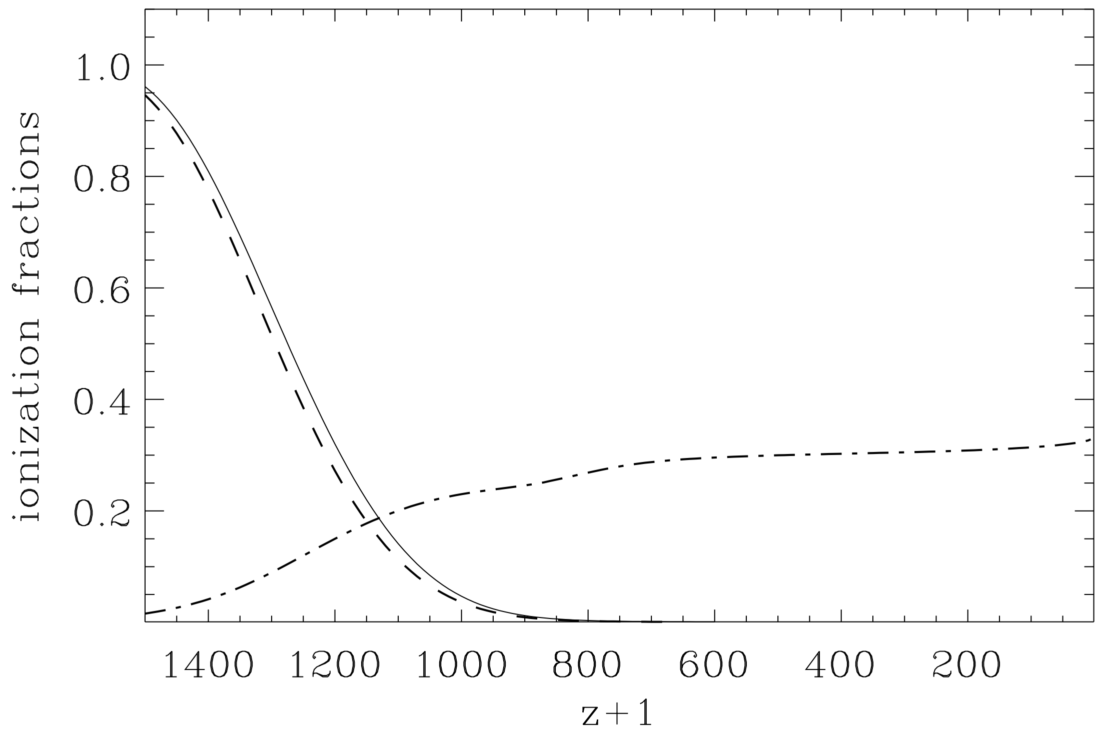
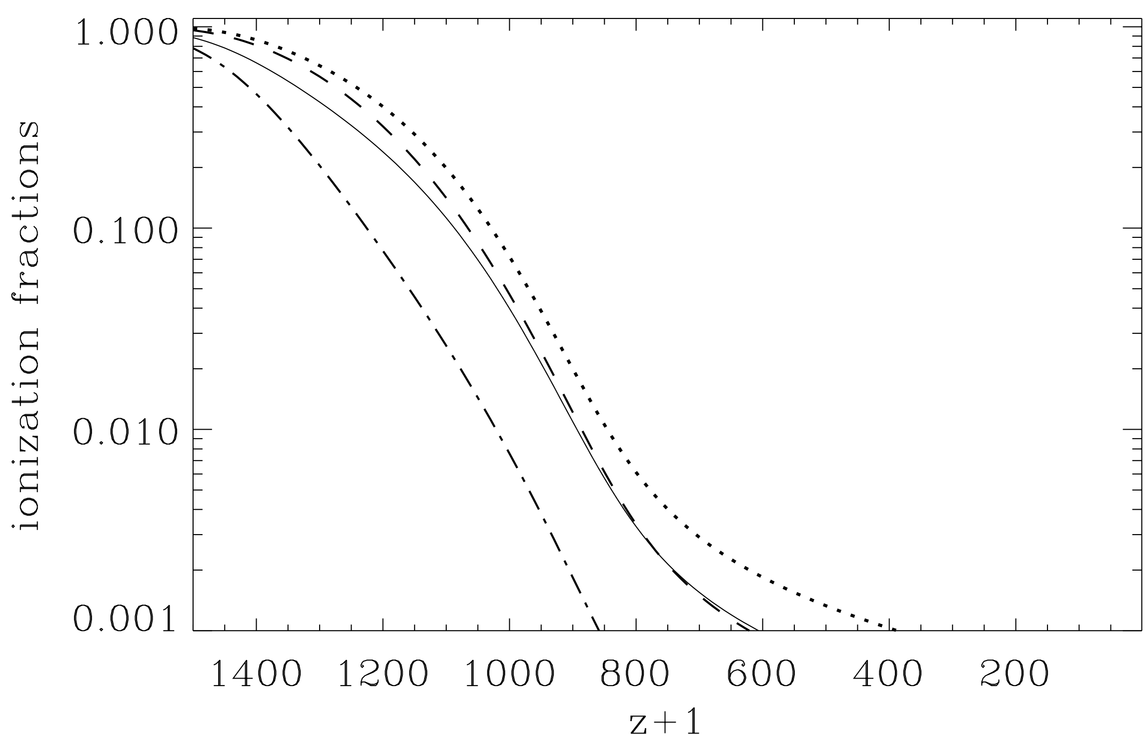


Fig. 1.— The ionization fraction for the model 1 (solid line) and model 2 (dashed line). Dot-dashed line draws the relative difference between the ionization fractions, x_{12}, for these models.



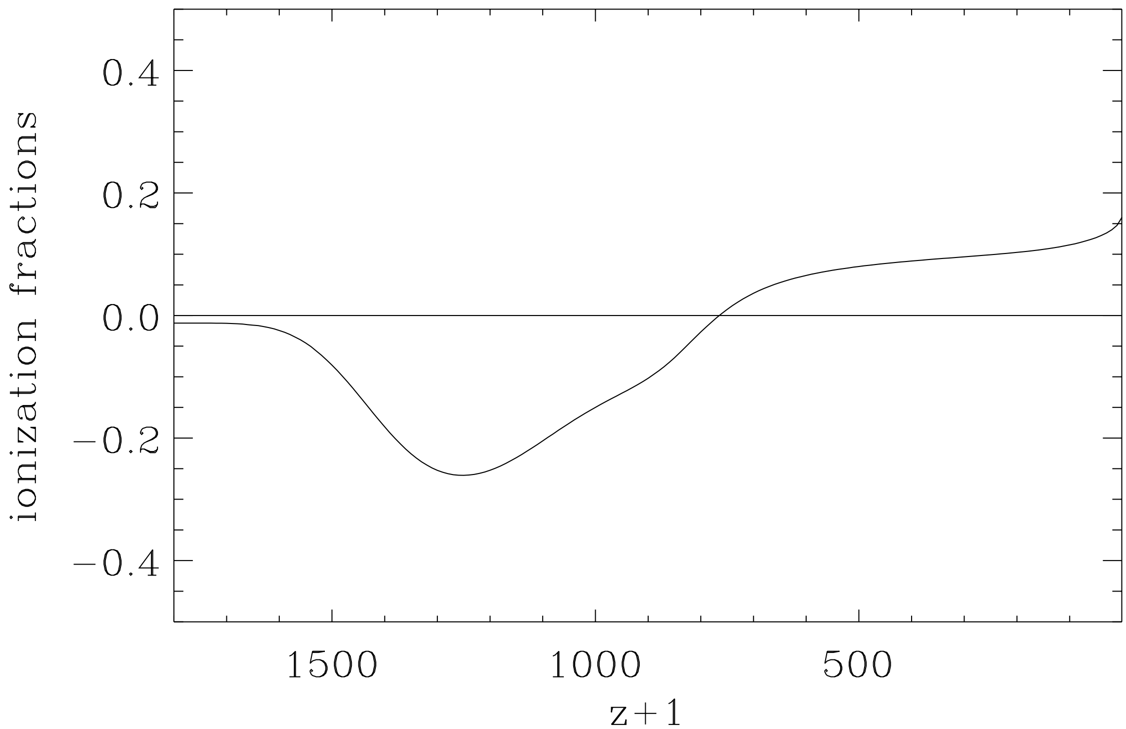


Fig. 3.— Redshift variations of the function $x_{13}(z)$ as given by (11).

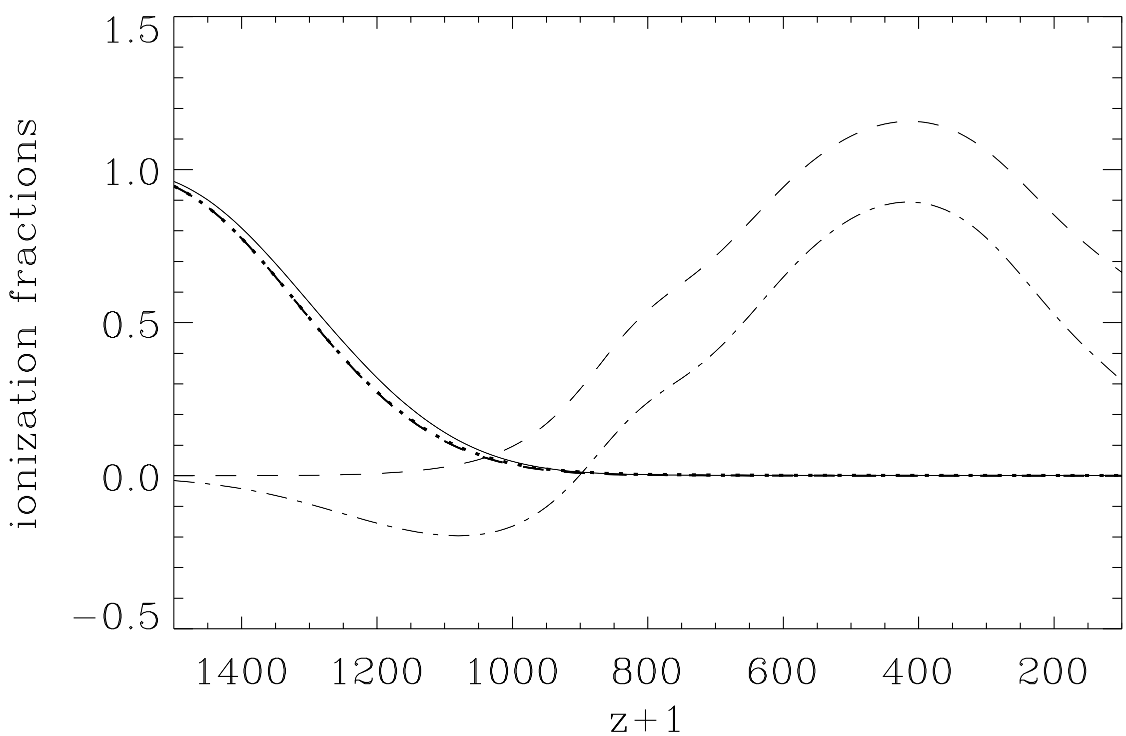


Fig. 4.— [illegible]

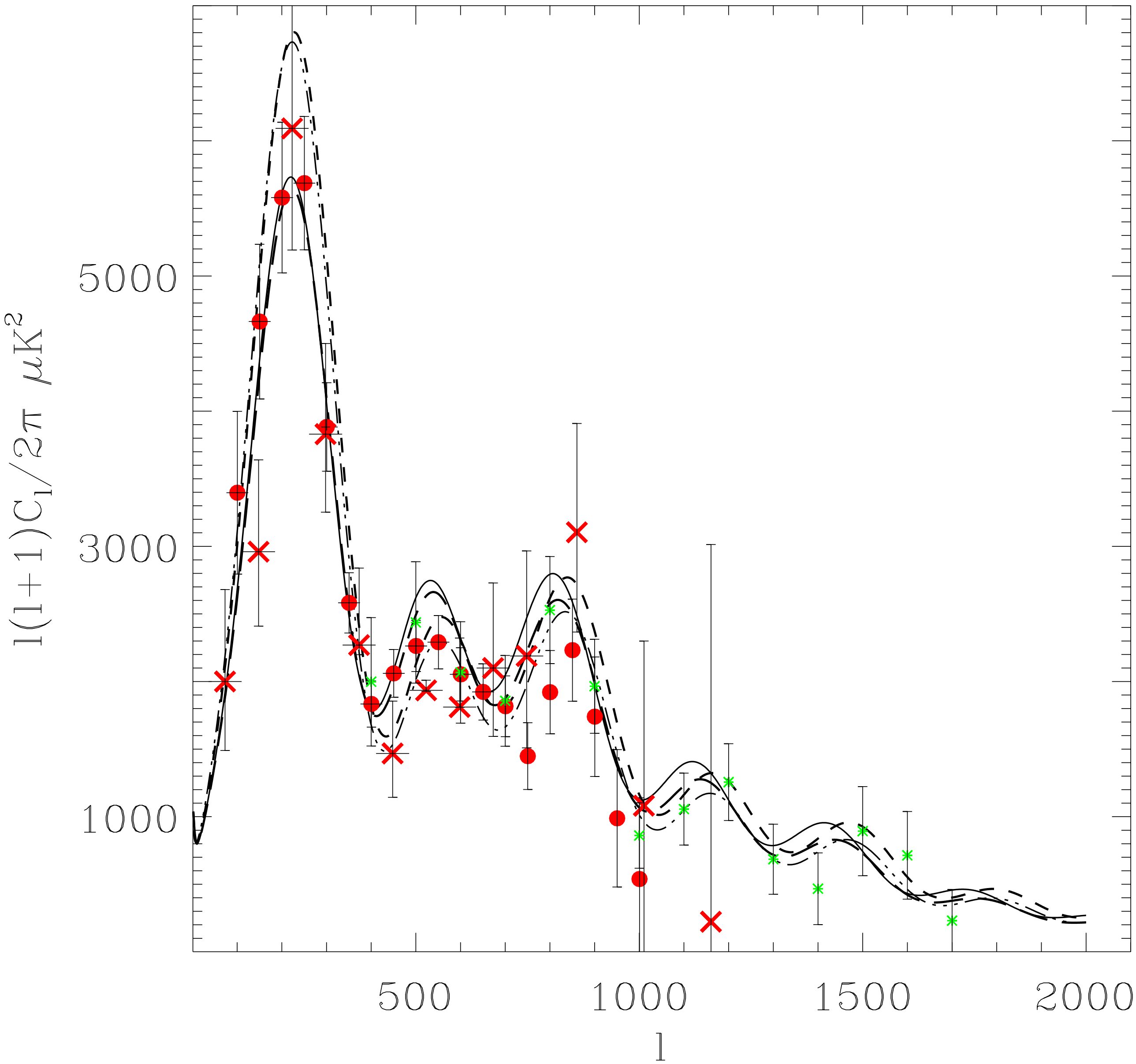


Fig. 5.— The CMB power spectrum for the model 1 (solid line), the model 2 (dashed line), the model 3 (dot-dashed line) and the model 4 (long dashed line) in comparison with the observed data (BOOMERANG – points, MAXIMA – large X, CBIM1 – small x.

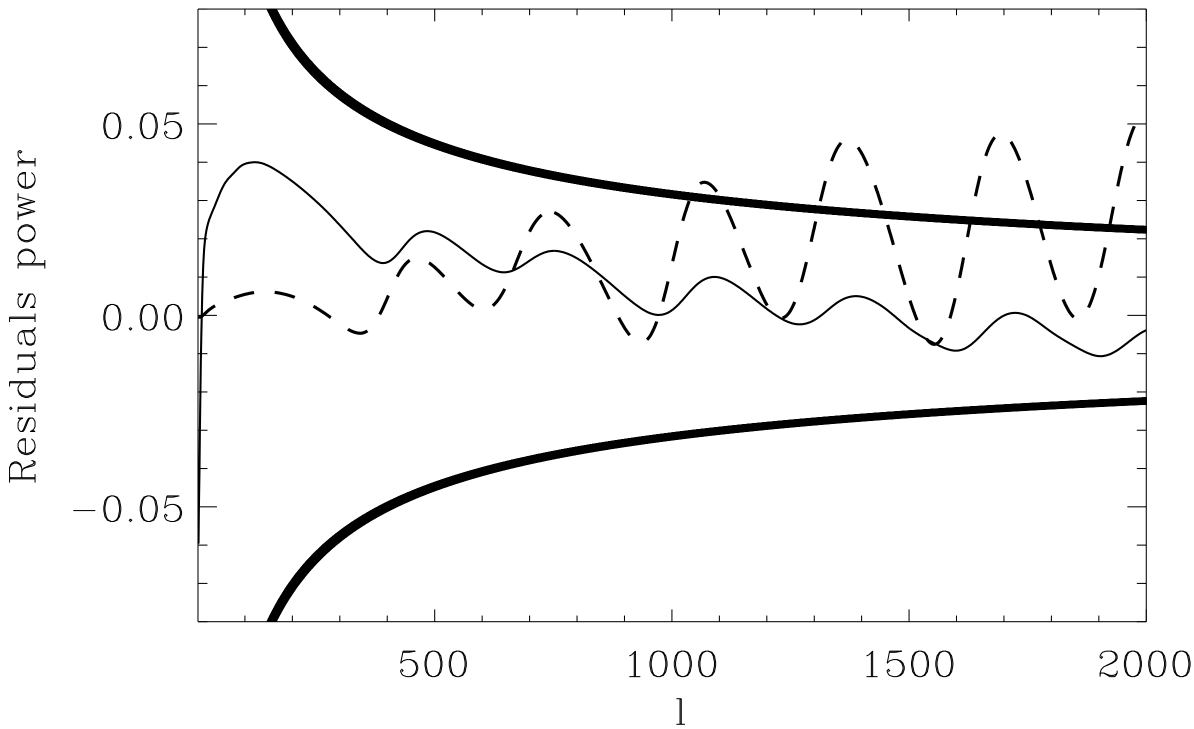


Fig. 6.— Functions $D_{13}(l)$ and $D_{24}(l)$ are drawn by solid and dashed lines, respectively. Thick solid line show expected errors for the PLANCK mission.

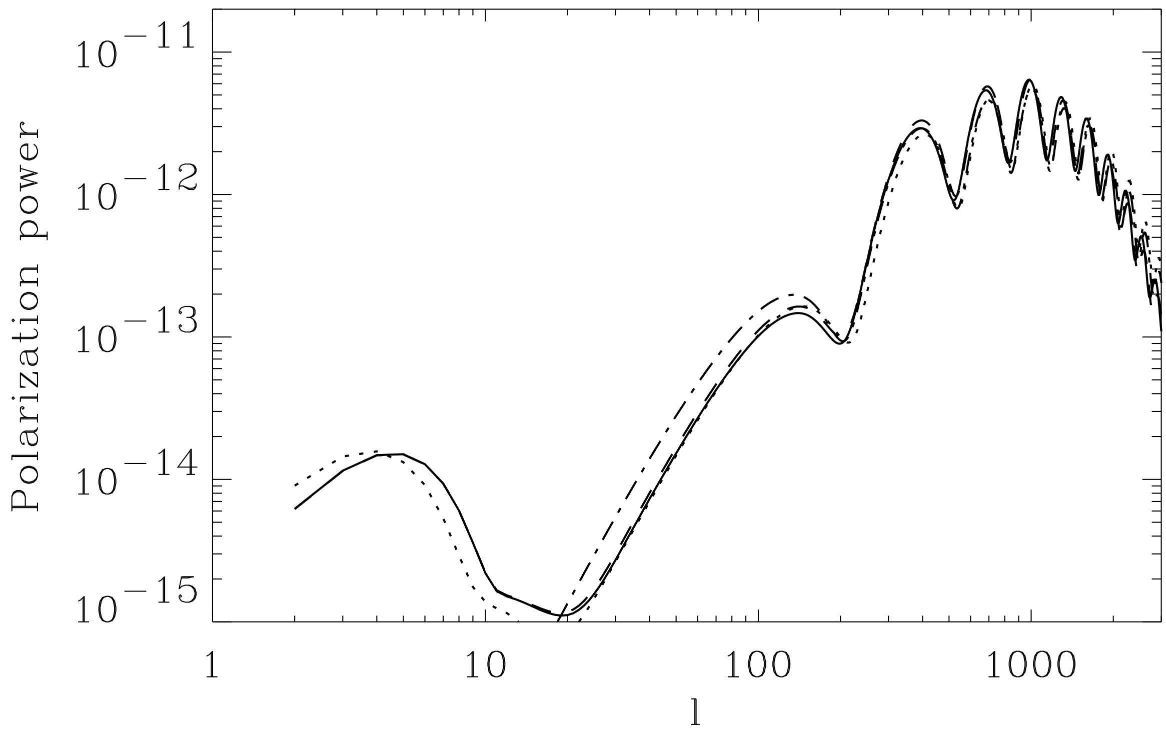


Fig. 7.— The power spectrum of the CMB polarization are plotted for the models 1 – 4 by solid, dotted, dashed and dot – dashed lines, respectively.

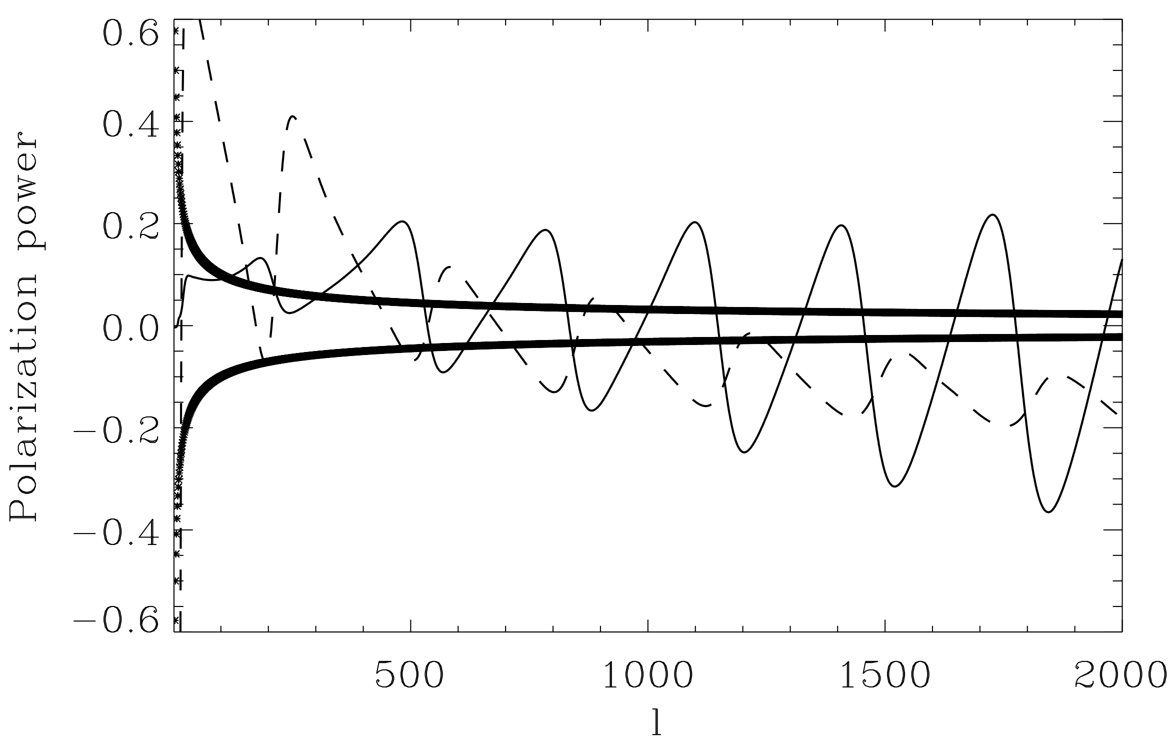


Table 1: χ^2 for observations and models

	BOOM	MAX	CBIM1	CBIM2	VSA
1	11.2	14.1	3.20	7.15	7.1
2	34.6	17.7	2.75	7.51	13.0
3	8.7	11.3	1.60	5.62	6.6
4	27.7	15.7	1.87	5.15	10.0